

BEST AVAILABLE COPY

DETERMINATION OF THE MECHANICS OF PROJECTILE  
PENETRATION OF NON-WOVEN STRUCTURES

AD 677523

Russell W. Ehlers  
Paul J. Angelo, Jr.

BEST AVAILABLE COPY

LOWELL TECHNOLOGICAL INSTITUTE RESEARCH FOUNDATION  
Lowell, Massachusetts

Final Report

Contract No. DA19-129-QM-1935 (OI 6037-62)

Project No. 7-80-05-001

January 1964

Reproduced by the  
CLEARINGHOUSE  
for Federal Scientific & Technical  
Information Springfield Va. 22151

DDC  
RECEIVED  
NOV 19 1968  
B

Prepared for  
Quartermaster Research and Engineering Command  
Natick, Massachusetts

THIS DOCUMENT HAS BEEN APPROVED FOR  
PUBLIC RELEASE AND SALE; ITS DISTRIBUTION  
IS UNLIMITED.

BEST AVAILABLE COPY

53

## ACKNOWLEDGMENT

We wish to express our sincere appreciation for the many helpful and valuable suggestions we received in the course of our investigation from Mr. Roy C. Laible, Dr. W. E. C. Yelland, Mr. William Cowie, Mr. Anthony Alesi and Mr. Elliott A. Snell of the Quartermaster Research and Engineering Command, Natick, Massachusetts.

We are also extremely grateful to the following fiber producers for their most generous contribution of small quantities of the various fibers used in the course of this study: E. I. duPont deNemours and Company, Incorporated, Dow Chemical Company, and Union Carbide Chemicals Company.

We are especially indebted to Assistant Professor Stephen J. Bodor of the Lowell Technological Institute faculty who developed the mathematical model with the able assistance of Associate Professor David H. Pfister who acted as statistician.

CONTENTS

	Page
1.0 INTRODUCTION	1
2.0 PREPARATION OF FELTS	3
2.1 Needle Nomenclature	7
2.2 Fiber Locker Details	7
3.0 BALLISTIC TESTS	8
4.0 EXPERIMENTAL	9
5.0 LOW SPEED PENETRATION TESTS	20
6.0 AIR PERMEABILITY TESTS ON SELECTED FELTS	24
7.0 EFFECT OF PRESSING ON BALLISTIC RESISTANCE	26
8.0 PERMANENCE OF THICKNESS AFTER PRESSING	28
9.0 COMPARISON OF EXPERIMENTAL FELT WITH COMMERCIALY PRODUCED FELT	30
10.0 EFFECT OF PLATING A HIGH TENACITY NYLON FIBER FELT WITH TWO PERCENTAGES OF POLYPROPYLENE FIBER	32
11.0 EFFECT OF DECETEX-104 ON BALLISTIC PROPERTIES OF HIGH TENACITY NYLON FIBER FELT	34
12.0 EFFECT OF SYTON ON BALLISTIC PROPERTIES OF NYLON FELT	35
13.0 DEVELOPMENT OF MATHEMATICAL MODEL	36
14.0 MATHEMATICAL MODEL	38
14.1 Example Illustrating Application of Formula	39
14.2 Analysis of Variance	40

CONTENTS (contd)

	Page
15.0 CONCLUSIONS	44
16.0 RECOMMENDATION FOR FUTURE STUDY	46

BEST AVAILABLE COPY

# TABLES

BEST AVAILABLE COPY

		Page
I	Results of Ballistic Tests - Dacron	11
II	Results of Ballistic Tests - Nylon	13
III	Results of Ballistic Tests - Orlon	16
IV	Results of Ballistic Tests - Zefran	17
V	Results of Ballistic Tests - Dynel	18
VI	Results of Ballistic Tests - Other Fibers	19
VII	Results of Low Speed Puncture Tests on Selected Samples	22
VIII	Results of Air Permeability Tests on Selected Samples	25
IX	Golden Caprolan High Tenacity Tire Cord Fiber Felt Pressed to Three Different Thicknesses and V-50 Tested	27
X	Effect of Pressing and Permanence of Thickness Obtained After 3 Weeks Storage at 70°F and 65% R.H.	29
XI	Comparison of Commercially Produced Felt and Felt Produced Experimentally at Lowell Technological Institute Research Foundation	31
XII	Effect of Plating a High Tenacity Nylon Fiber Felt With Two Percentages of Polypropylene Fiber	33
XIII	Breaking Strength, Elongation and Work Index of Major Fibers Evaluated	41

## FIGURES

	Page
1. Carding Machine	5
2. Fiber Locker	6
3. Instron Machine Adapter for Low Speed Penetration Test	21

BEST AVAILABLE COPY

LOWELL TECHNOLOGICAL INSTITUTE RESEARCH FOUNDATION  
Lowell, Massachusetts

FINAL REPORT

DETERMINATION OF THE MECHANICS OF PROJECTILE

PENETRATION OF NON-WOVEN STRUCTURES

1.0 INTRODUCTION

The primary objective of this study was to establish the interaction of fiber and non-woven fiber felt properties to projectile resistance or impact.

For the purpose of this work, the non-woven structures were needed synthetic fiber felts with slight modifications in special instances. Projectile penetration refers to a ballistic technique used by the U. S. Army for the acceptance testing of armor vests and frequently called a "V-50" test.

Such fiber properties as length, denier, crimp, tenacity, elongation have been considered in the evaluation. Felt properties such as thickness, areal density (weight per square yard), air permeability, resistance to low speed penetration and methods of felt preparation constitute additional variables which have been examined relative to their contribution to ballistic resistance.

Finally, some thought has been given to the production of a superior ballistic felt with consideration given to the weight, bulk water proofness and method of felt manufacture.

As this investigation began, no references were found in the literature relative to the ballistic resistance of non-woven structures although it is conceded that a number of such materials have been screened by various agencies of the military as potential armor materials.

The ultimate goal of this program was the establishment of a mathematical relationship between fiber and felt properties and ballistic resistance as determined by the V-50 test.

The program was restricted to synthetic fibers in that controlled fiber properties were available. A fiber locker or needle felting machine was selected as the ideal medium for the manufacture of the non-woven structures inasmuch as a felt is formed mechanically without regard to chemical binders, adhesives, etc. which conceivably alter both fiber and felt properties making it more difficult to assess the true significance of each property.

BEST AVAILABLE COPY

## 2.0 PREPARATION OF FELTS

Various techniques were devised in the course of study in regard to the preparation of the felt material.

Based on preliminary screening of needled felts for ballistic properties by the project officer, an areal density of approximately 38 oz/sq yd was decided upon as an effective weight panel which might conceivably provide sufficient ballistic resistance to screen a number of different fibers in a range of deniers and lengths.

Initially it was felt necessary to determine whether the carded webs should be laid unidirectional or cross laid prior to needling. In an effort to establish the effect on ballistic properties, two felts were prepared as identical as possible excepting that one was made with the webs unidirectional, the other with the webbings alternately crossed at 90° to each other. When ballistic ratings failed to show a significant advantage to the cross laid felt (see Felts Code A and Code B Table I), it was decided to adopt the more convenient unidirectional type.

Basically, the felt-making technique consisted of weighing out the fiber in two ounce quantities, spreading the fiber to a uniform depth and width on the feed apron of a woolen type carding machine and winding the resultant web on a drum approximately 45

inches in circumference (see figure 1).

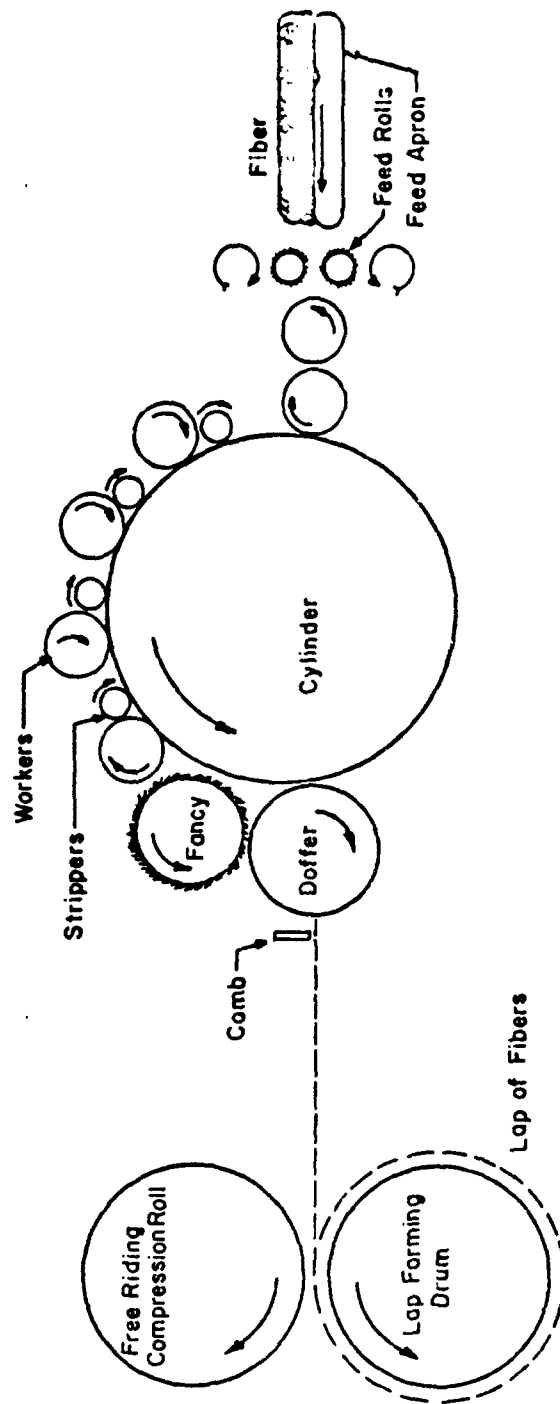
A free ride compression drum was placed on the winding drum to compact the superimposed webbings. The lap of fiber was then cut from the drum and fed directly to the fiber locker (experimental size) or needle felting machine (see figure 2). After needling the bat once on each side, the felt is doubled over and needled once again on each side. A number of similarly constructed felts are then needled together until the desired weight is obtained. The fineness of the fiber appreciably influences the growth of the bat upon compaction; the finer the fiber, the greater the growth. In the case of 1 - 2 denier fibers, resistance to needling became so great it prevented us from reaching the desired weight. In this case, the felting needles break and finer needles with fewer barbs are indicated.

In order to establish the effect of needling alone on the ballistic properties, another felt forming technique was devised. In this case a single lap representing the entire weight of the panel desired was formed, compressed by cold callendering between sheets of Kraft paper using 63 lbs/sq in nip pressure and then needled the desired number of times.

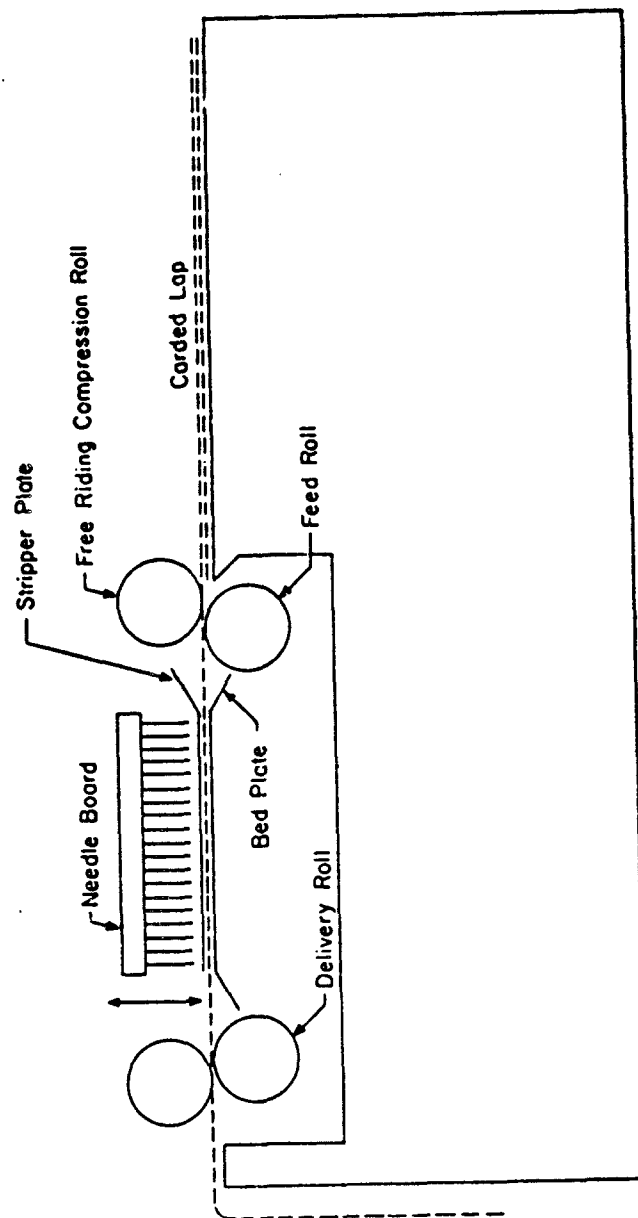
The compression of the lap became necessary so as to pass the material between the bed plate and stripper plate of the fiber locker (see figure 2).

BEST AVAILABLE COPY

BEST AVAILABLE COPY



CARDING MACHINE  
FIGURE 1



FIBER LOCKER  
FIGURE 2

BEST AVAILABLE COPY

In this manner a number of felts were prepared with approximately equal weight of fiber but with three, six, and ten passes through the needling machine.

Throughout the experiments the same type felting needle was employed and the operating conditions and settings of the fiber locker were maintained.

### 2.1 Needle Nomenclature

Manufactured by The Torrington Company  
Boston, Massachusetts

Description: 77-1174-00-8

15x18x32x3R

Type A, Ball Point

No kick-up Barb

### 2.2 Fiber Locker Details

Needleboard - Hi density type -  $25 \times 23 = 575$  needles

Advance - .175 inches per stroke

Speed - 200 strokes per minute

Penetrations/sq in/pass - 260

Depth of Penetration - 5/16 inches through bedplate

BEST AVAILABLE COPY

### 3.0 BALLISTIC TESTS

All ballistic tests were subcontracted to the Victory Plastics Company, Hudson, Massachusetts who are adequately equipped and staffed to conduct the V-50 type ballistic test.<sup>1/</sup>

In the V-50 test, 0.22 caliber steel missiles of special shape and commonly referred to as fragment simulators are fired from a rigidly mounted rifle at a panel of the material under test. Electronic means are provided for the determination of the velocities of the projectile which in turn is varied by weighing out varying amounts of the explosive powder. The ballistic resistance reported in feet per second is mathematically determined as the means of velocities, within a narrow specified range, at which 50% of the missiles are in effect stopped by the test panel.

<sup>1/</sup> MIL-STD-662 28 June 1961

#### 4.0 EXPERIMENTAL

Tables I through VI describe 106 felts manufactured from ten different fibers. Unless otherwise indicated, all fibers were crimped. It should be noted that staple fibers, except in isolated cases, are supplied only in crimped form. Furthermore, the amount of crimp is varied from one type of fiber to another and also between deniers of the same fiber. Accurate crimp measurements are difficult to obtain and could best be supplied by the fiber producer. No direct association could be established between crimp and ballistic resistance in the mathematical model, so that crimp has been deleted from the tables.

Thickness, as recorded in the tables, represents an average of ten thickness measurements conducted on a 12"x12" felt at various locations using a standard thickness gauge with a 1.129 inch diameter presser foot and a ten ounce weight.

Weight in oz per square yard have been determined by weighing a 12"x12" felt in grams and expressing the weight on a square yard basis in ounces.

The number of passages of the felt through the needle felting machine can be determined by dividing the total penetrations per square inch (from the table) by 260.

Some of the nylon felts (Codes 4U-2, 4T-2, 4W, 4X, and

4y) were heatset and pressed so as to reduce the over-all thickness to a maximum of one-third of an inch. Pressing was accomplished by pre-heating the fiber panel between steel plates in an oven at 335°F for ten minutes and immediately placing the preheated assembly in a flat press at 310°F. A pressure of 50 pounds per square inch was sufficient to press the felts to .187 inch stop and the time held was five minutes per panel.

Single fiber tenacities and elongation were determined in accordance with ASTM Test Method D540.

Values reported in Table XIII are averages obtained from 40 fiber breaks using an Instron machine with a crosshead speed of 1/2 inch per minute and a chart speed of 2 inches per minute. A nominal gauge length of one inch was used as a standard so that no differences in elongation would occur due to changes in gauge length.

TABLE I  
RESULTS OF BALLISTIC TESTS

DACRON

Code	Denier	Length Inches	Thick- ness Inches	Weight Oz Per Sq Yd	Penetra- tions Per Sq In	V-50 Ft/ Sec	Comments
XX	1.5	1.5	0.385	35.0	8840	691	
4D	1.5	1.5	0.221	19.1	520	467	Could not in- crease weight as needles broke
4E	1.5	1.5	0.154	12.9	1040	441	Could not in- crease weight as needles broke
A	3.0	1.5	0.333	35.4	7280	706	Type 5400
B	3.0	1.5	0.365	35.5	7280	724	Crosslaid webs Type 5400
C	3.0	1.5	0.458	38.1	7280	778	
R	3.0	1.5	0.399	35.1	7280	712	
S	3.0	1.5	0.416	50.9	7280	746	
T	3.0	1.5	0.326	22.3	7280	707	
GGG	3.0	1.5	0.433	38.3	780	841	Type 5400
HHH	3.0	1.5	0.357	41.3	1560	752	Type 5400
III	3.0	1.5	0.302	38.1	2600	705	Type 5400
MMM	3.0	1.5	0.447	32.0	780	869	
NNN	3.0	1.5	0.426	28.6	1560	771	
OOO	3.0	1.5	0.263	25.5	2600	697	

All Type 54 except those indicated as 5400.

TABLE I (Contd)

<u>Code</u>	<u>Denier</u>	<u>Length Inches</u>	<u>Thick- ness Inches</u>	<u>Weight Oz Per Sq Yd</u>	<u>Penetra- tions Per Sq In</u>	<u>V-50 Ft/ Sec</u>	<u>Comments</u>
H	3.0	2.5	0.439	35.1	7280	763	
H	3.0	3.0	0.346	38.2	7280	725	
G	3.0	4.5	0.462	38.1	7280	774	
JJJ	3.0	4.5	0.411	32.0	780	834	
KKK	3.0	4.5	0.300	28.6	1560	790	
LLL	3.0	4.5	0.253	25.5	2600	689	
D	4.5	1.5	0.564	38.3	6760	841	
PPP	4.5	1.5	0.512	38.1	780	904	
QQQ	4.5	1.5	0.401	38.1	1560	784	
RRR	4.5	1.5	0.334	35.1	2600	749	
H	6.0	1.5	0.432	38.1	5720	781	
O	6.0	3.0	0.479	35.2	5720	797	
Q	6.0	4.5	0.500	38.1	5720	794	

All Type 54.

TABLE II  
RESULTS OF BALLISTIC TESTS  
NYLON

<u>Code</u>	<u>Type</u>	<u>Den.</u>	<u>Lgth</u> <u>In.</u>	<u>Thick-</u> <u>ness</u> <u>In.</u>	<u>Wgt</u> <u>Oz/</u> <u>Sq Yd</u>	<u>V-50</u> <u>Ft/</u> <u>Sec</u>	<u>Penetra-</u> <u>tions</u> <u>Per Sq In</u>	<u>Comments</u>
BB	200	1.5	1.5	0.459	41.3	842	3640	
FF	201	1.5	1.5	0.348	35.1	767	3640	
P	420	2.3	1.5	0.426	35.2	835	7280	
W	200	3.0	1.5	0.485	38.3	902	7280	
J	201	3.0	2.0	0.427	44.5	853	7280	
AA	201	3.0	2.0	0.381	38.2	858	7280	
MM	201	3.0	2.0	0.497	41.4	830	7280	
F	200	3.0	2.5	0.534	38.3	896	7280	
X	200	3.0	3.0	0.446	44.6	853	7280	
Y	200	3.0	3.0	0.437	38.1	850	7280	
EE	200	3.0	4.5	0.413	41.2	806	7280	
BBB	200	3.0	4.5	0.540	41.5	826	780	
"O"	100	6.0	2.0	0.546	38.1	961	1560	Random Orientation of Webs
"Q"	100	6.0	2.0	0.531	34.9	809	1560	Pad sprayed with Syton (2%)
"R"	100	6.0	2.0	0.428	31.8	863	1560	Fiber sprayed with Syton - 2% on weight of fiber
"P"	100	6.0	2.0	0.547	35.2	839	1560	

TABLE II (Contd)

<u>Code</u>	<u>Type</u>	<u>Den.</u>	<u>Lgth In.</u>	<u>Thick- ness In.</u>	<u>Wgt Oz/ Sq Yd</u>	<u>V-50 Ft/ Sec</u>	<u>Penetra- tions Per Sq In</u>	<u>Comments</u>
Z	101	6.0	3.0	0.468	41.4	896	5720	
K	201	6.0	3.0	0.498	54.2	872	5720	
LL	201	6.0	3.0	0.518	38.1	923	5720	
AAA	101	6.0	3.0	0.498	38.1	904	780	
DDD	201	6.0	3.0	0.649	54.0	998	780	
EEE	201	6.0	3.0	0.488	57.1	866	1560	
FFF	201	6.0	3.0	0.483	51.0	913	2600	
4U-1	702	6.0	3.0	0.681	49.7	<u>1129</u>	1040	High tenacity in- dustrial type fila- ment yarn cut up
4U-2	702	6.0	3.0	0.340	53.8	<u>1048</u>	1040	Same as 4U-1 only pressed
4V-1	702	6.0	3.0	0.413	34.9	<u>989</u>	1040	High tenacity chop- ped yarn at lower weight than 4U-1
4V-2	702	6.0	3.0	0.263	38.5	<u>1007</u>	1040	Same as 4V-1 only pressed
4T-1	60	6.0	3.25	0.576	53.9	<u>1029</u>	1560	
4T-2	60	6.0	3.25	0.285	53.9	<u>1028</u>	1560	Same as 4T-1 only pressed
DD	101	6.0	4.5	0.415	44.6	828	5720	

TABLE II (Contd)

<u>Code</u>	<u>Type</u>	<u>Den.</u>	<u>Lgth</u> <u>In.</u>	<u>Thick-</u> <u>ness</u> <u>In.</u>	<u>Wgt</u> <u>Oz/</u> <u>Sq Yd</u>	<u>V-50</u> <u>Ft/</u> <u>Sec</u>	<u>Penetra-</u> <u>tions</u> <u>Per Sq In</u>	<u>Comments</u>
CCC	101	6.0	4.5	0.473	57.1	854	1040	Pressed 5 min @ 300°F 100 lb/in <sup>2</sup> (Not remeasured)
CC	101	6.0	6.5	0.444	38.3	873	5720	
4W	6	--	3.0	0.277	51.0	1091	1560	Pressed after needling. Golden Caprolan Tire Cord Material
4X	--	--	3.0	0.274	53.9	1013	1560	Style 1329 Star Woolen. Pressed
4Y	--	--	3.0	0.281	58.3	1045	1560	Style 1328 Star Woolen. Pressed

BEST AVAILABLE COPY

TABLE III  
RESULTS OF BALLISTIC TESTS  
ORLON

<u>Code</u>	<u>Denier</u>	<u>Length Inches</u>	<u>Thick- ness Inches</u>	<u>Weight Oz Per Sq Yd</u>	<u>V-50 Ft/ Sec</u>	<u>Penetra- tions Per Sq In.</u>	<u>Comments</u>
ZZ	1.0	1.5	0.546	38.0	695	5720	2 pieces of felt treated as one
YY	2.0	1.5	0.447	32.0	773	5720	
E	3.0	1.5	0.651	38.1	836	7280	
U	3.0	1.5	0.600	47.8	857	7280	
V	3.0	1.5	0.436	44.7	765	7280	
PP	3.0	3.0	0.416	38.2	753	7280	
QQ	3.0	4.5	0.427	34.6	767	7280	
NN	6.0	1.5	0.533	35.1	696	5720	
OO	6.0	3.0	0.466	38.1	742	5720	
I	6.0	4.5	0.604	41.5	772	5720	

All Type 42

TABLE IV  
RESULTS OF BALLISTIC TESTS

ZEFRAN

<u>Code</u>	<u>Denier</u>	<u>Length Inches</u>	<u>Thick- ness Inches</u>	<u>Weight Oz Per Sq Yd</u>	<u>V-50 Ft/ Sec</u>	<u>Penetra- tions Per Sq In</u>
VV	3.0	1.5	0.349	32.0	722	7280
WC	3.0	1.5	0.509	35.1	791	780
SS	3.0	2.0	0.460	38.2	744	7280
UU	2.0	2.5	0.377	38.0	742	7280
TT	6.0	1.5	0.431	35.1	728	5720
SSS	6.0	1.5	0.368	28.7	710	780
TTT	6.0	1.5	0.284	25.6	606	1560
UUU	6.0	1.5	0.254	25.5	581	2600
W	6.0	2.0	0.451	38.0	713	5720
VVV	6.0	2.0	0.397	31.9	706	780
WWW	6.0	2.0	0.312	31.9	668	1560
XXX	6.0	2.0	0.263	28.6	589	2600
RR	6.0	2.5	0.414	38.0	678	5720
YYY	6.0	2.5	0.400	34.9	684	780
ZZZ	6.0	2.5	0.312	31.7	616	1560
AA	6.0	2.5	0.278	31.9	604	2600
JJ	6.0	3.0	0.293	22.3	492	780

BEST AVAILABLE COPY

TABLE V  
RESULTS OF BALLISTIC TESTS

DYNEL							
<u>Code</u>	<u>Type</u>	<u>Denier</u>	<u>Length Inches</u>	<u>Thick- ness Inches</u>	<u>Weight Oz Per Sq Yd</u>	<u>V-50 Ft/ Sec</u>	<u>Penetra- tions Per Sq In.</u>
4N	180	3.0	1.5	0.467	28.7	617	4160
4I	180	3.0	1.5	0.444	31.8	728	5720
4H	60	3.0	3.0	0.466	35.0	739	5720
4F	180	6.0	1.5	0.527	31.9	770	5720
4G	180	6.0	3.0	0.489	31.9	747	5720
4J	197	15.0	2.5	0.481	35.0	358	5720
4L	197	15.0	4.0	0.503	47.6	384	5720
4K	60	24.0	2.5	0.601	38.1	670	5720
4M	60	24.0	4.0	0.554	41.4	737	5720

BEST AVAILABLE COPY

TABLE VI  
RESULTS OF BALLISTIC TESTS  
OTHER FIBERS

<u>Code</u>	<u>Fiber</u>	<u>Denier</u>	<u>Length Inches</u>	<u>Thick- ness Inches</u>	<u>Weight Oz Per Sq Yd</u>	<u>V-50 Ft/ Sec</u>	<u>Penetra- tions Per Sq In.</u>
L	Polypropylene	3.0	2.5	0.426	38.3	841	7280
GG	Verel	3.0	1.5	0.409	41.2	690	7280
HH	Verel	24.0	2.0	0.471	41.4	488	5720
II	Acetate	3.0	1.125	0.386	35.2	464	7280
JJ	Acetate	12.0	3.0	0.432	41.2	561	5720
KK	Viscose	5.5	3.0	0.512	38.2	761	5720
4S	Vinal	3.0	2.0	0.286	19.3	737	1820

BEST AVAILABLE

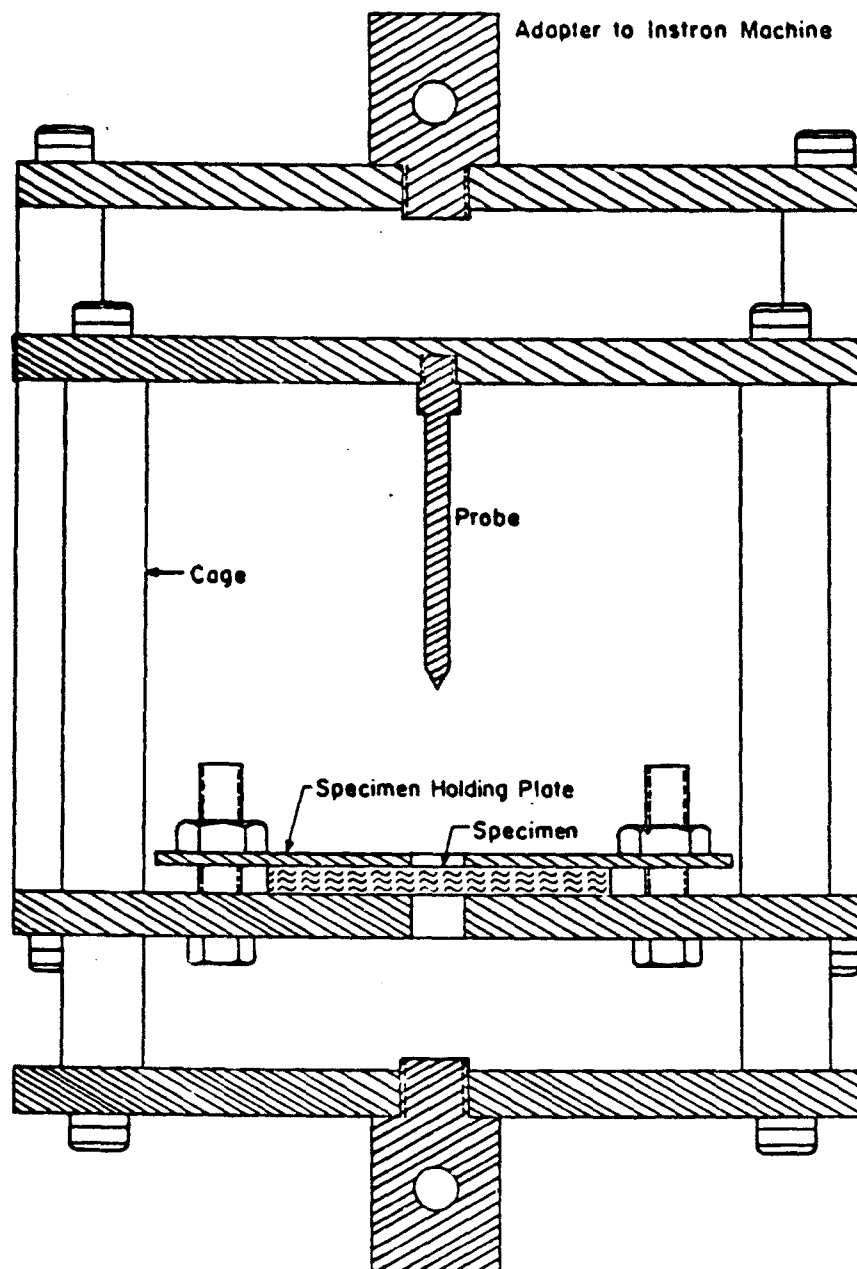
## 5.0 LOW SPEED PENETRATION TESTS

In order to determine whether a simple laboratory test could differentiate between good and bad felts in regard to ballistic resistance, a number of the felts were subjected to a relatively low speed penetration or burst type of test.

For this purpose a compression type cage adaptable to a full size Instron machine was devised (see figure 3). The cage consisted of a specimen clamping device and stylus appropriately ground to obtain a complete penetration of the range of felts tested.

The probe was made of 1/4" hardened steel rod ground to a sharp point with a 3/8 inch taper. A crosshead speed of 10 inches per minute was employed for all punctures with the force recorded in pounds (see Table VII).

BEST AVAILABLE COPY



INSTRON MACHINE ADAPTER for LOW SPEED PENETRATION TEST

FIGURE 3

TABLE VII  
RESULTS OF LOW SPEED PUNCTURE TESTS ON SELECTED SAMPLES

<u>Code</u>	<u>Fiber</u>	<u>Denier</u>	<u>Length Inches</u>	<u>Thick- ness Inches</u>	<u>Weight Oz Per Sq Yd</u>	<u>V-50 Ft/ Sec</u>	<u>Lbs Force to Puncture</u>
II	Acetate	3.0	1.125	0.386	35.2	464	48.8
JJ	Acetate	12.0	3.0	0.432	41.2	561	53.0
GG	Verel	3.0	1.5	0.409	41.2	698	85.2
000	Dacron	3.0	1.5	0.263	25.5	697	92.0
III	Dacron	3.0	1.5	0.302	38.1	705	124.6
A	Dacron	3.0	1.5	0.333	35.4	706	97.1
T	Dacron	3.0	1.5	0.326	22.3	707	80.0
R	Dacron	3.0	1.5	0.399	35.1	712	133.0
B	Dacron	3.0	1.5	0.365	35.5	724	114.0
M	Dacron	3.0	3.0	0.346	38.2	725	154.0
S	Dacron	3.0	1.5	0.416	50.9	745	175.0
HHH	Dacron	3.0	1.5	0.357	41.3	752	134.0
H	Dacron	3.0	2.5	0.439	35.1	763	144.0
NNN	Dacron	3.0	1.5	0.426	28.6	771	100.0
C	Dacron	3.0	1.5	0.458	38.1	778	137.0
N	Dacron	6.0	1.5	0.432	38.1	781	126.0
EE	Nylon	3.0	4.5	0.413	41.2	806	155.0
DD	Nylon	6.0	4.5	0.415	44.6	828	167.0
MM	Nylon	3.0	2.0	0.497	41.4	830	180.0

TABLE VII (Contd)

<u>Code</u>	<u>Fiber</u>	<u>Denier</u>	<u>Length Inches</u>	<u>Thick- ness Inches</u>	<u>Weight Oz Per Sq Yd</u>	<u>V-50 Ft/ Sec</u>	<u>Lbs Force to Puncture</u>
D	Dacron	4.5	1.5	0.564	38.3	841	147.0
X	Nylon	3.0	3.0	0.446	44.6	853	190.5
MM	Dacron	3.0	1.5	0.447	32.0	869	116.0
CC	Nylon	6.0	6.5	0.444	38.3	873	185.0

Puncture tests performed on Instron machine equipped with compression type cage with specimen clamping device and probe.

Crosshead speed 10 inches per minute.

Probe made of 1/4" hardened steel roll ground to a sharp point with a 3/8 inch taper.

BEST AVAILABLE COPY

## 6.0 AIR PERMEABILITY TESTS ON SELECTED FELTS

Air Permeability measurements were conducted on 13 felt samples once again to maintain whether a correlation might exist between a standard laboratory technique and ballistic resistance. The results obtained appear in Table VIII.

TABLE VIII  
RESULTS OF AIR PERMEABILITY TESTS ON SELECTED SAMPLES

<u>Code</u>	<u>Fiber</u>	<u>Denier</u>	<u>Length Inches</u>	<u>Thick- ness Inches</u>	<u>Weight Oz Per Sq Yd</u>	<u>V-50 Ft/ Sec</u>	<u>Cu<sub>2</sub>Ft Air/ Ft<sup>2</sup>/Min</u>
S	Dacron	3.0	1.5	0.416	50.9	746	22.8
X	Nylon	3.0	3.0	0.446	44.6	853	26.1
CG	Verel	3.0	1.5	0.409	41.2	690	27.2
M	Dacron	3.0	3.0	0.346	38.2	725	28.7
MM	Nylon	3.0	2.0	0.497	41.4	830	30.4
EE	Nylon	3.0	4.5	0.413	41.2	806	31.0
II	Acetate	3.0	1.125	0.386	35.2	464	35.7
H	Dacron	3.0	2.5	0.439	35.1	763	37.3
A	Dacron	3.0	1.5	0.333	35.4	706	40.4
DDD	Nylon	6.0	3.0	0.649	54.0	998	42.4
CC	Nylon	6.0	6.5	0.444	38.3	873	63.0
N	Dacron	6.0	1.5	0.432	38.1	781	76.7
JJ	Acetate	12.0	3.0	0.432	41.2	561	97.0

## 7.0 EFFECT OF PRESSING ON BALLISTIC RESISTANCE

For the purpose of this test, a single felt Code 5A-1, -2, -3, (see Table IX) was prepared from Golden Caprolan High Tenacity Nylon Fiber. The felt was purposely made heavy and thick, heated and pressed to three different dimensions. Thickness measurements were made both before and after pressing in the same places in the felt. Further examples of the effect of pressing on the ballistic properties of felts were obtained on nylon felts 4U-1 & 2, 4V-1 & 2 and 4T-1 & 2 (Table II).

TABLE IX

GOLDEN CAPROLAN HIGH TENACITY TIRE CORD FIBER FELT  
PRESSED TO THREE DIFFERENT THICKNESSES AND V-50 TESTED

Fiber, 6 denier/3 inches, 12 crimps/inch

<u>Code</u>	<u>Before Pressing</u>		<u>After Pressing</u>		<u>V-50</u>
	<u>Thickness</u>	<u>Oz/Sq Yd</u>	<u>Thickness</u>	<u>Oz/Sq Yd</u>	
5A-1	0.642	66.6	0.396	65.3	1029
5A-3	0.604	62.3	0.284	60.2	952
5A-2	0.624	64.9	0.211	62.6	875

Felt 5A-1 pressed to 0.340 inch stops

Felt 5A-3 pressed to 0.240 inch stops

Felt 5A-2 pressed with 1500 lbs/sq in., no stops

Note: Felt 4W reported in Table II, Page 13 was prepared from the same fiber and was pressed from 0.665 inches to 0.277 inches (weight 51.0 oz/sq yd) with a resultant V-50 of 1091 ft/sec.

## 8.0 PERMANENCE OF THICKNESS AFTER PRESSING

For this test a commercially produced felt was heated and pressed to three different thicknesses (see Table X). The felts were allowed to stand three weeks under controlled laboratory conditions of 70°F and 65% R.H. then re-measured and ballistically tested.

100-100000-100000

TABLE X

EFFECT OF PRESSING AND PERMANENCE OF THICKNESS  
OBTAINED AFTER 3 WEEKS STORAGE AT 70°F AND 65% R. H.

Felt VEE 1349, 65% high tenacity nylon, 35% semi-dull crimpset nylon  
2" staple

<u>Code</u>	<u>Original Thickness</u>	<u>Original V-50 (QM) (Avg)</u>	<u>Pressed Thickness</u>	<u>Thickness After 3 Wks at 70°F and 65% R. H.</u>	<u>Growth (%)</u>	<u>Weight Oz per Sq Yd</u>	<u>V-50</u>
SH-1	0.559	1109	0.383	0.403	5.2	55.7	1031
SH-2	0.563	1109	0.329	0.349	5.7	55.7	974
SH-3	0.571	1109	0.249	0.264	6.1	57.0	990

## 9.0 COMPARISON OF EXPERIMENTAL FELT WITH COMMERCIALLY PRODUCED FELT

In order to investigate whether differences would be obtained between felt produced experimentally and commercially produced felt, a commercial felt was obtained and cut into four panels.

An experimental felt was then made from the same fiber blend and pressed with every effort made to duplicate the weight and thickness of the commercial felt. Table XI reviews the result of this comparison and also establishes the variability of V-50 values between two V-50 test ranges on the same felt.

BEST AVAILABLE COPY

COMPARISON OF COMMERCIALY PRODUCED FELT  
AND FELT PRODUCED EXPERIMENTALLY AT  
LOWELL TECHNOLOGICAL INSTITUTE RESEARCH FOUNDATION

**Blend:** 65% high tenacity bright uncrimped 6.0 denier, 3" staple nylo.  
35% normal tenacity, semi-dull, crimped 3 denier, 2" staple

<u>Code</u>	<u>Thickness Before Pressing</u>	<u>Weight Before Pressing</u>	<u>Thickness After Pressing</u>	<u>Weight After Pressing</u>	<u>Victory Plastics V-50</u>
5B-1	0.608	57.0	0.358	60.6	1005
5B-2	0.641	58.3	0.371	61.3	1056
5B-3	0.616	58.7	0.359	61.2	1070
5B-4	<u>0.638</u>	<u>60.3</u>	<u>0.359</u>	<u>63.5</u>	<u>1021</u>
Avg	0.626	58.6	0.362	61.6	1038

<u>Code</u>	<u>Thickness as Received</u>	<u>Weight as Received</u>	<u>QM V-50</u>	<u>Victory Plastics V-50</u>
5C-1	0.361	55.3	1098	1083
5C-2	0.353	56.4	1129	1077
5C-3	0.358	59.3	1083	1046
5C-4	<u>0.360</u>	<u>57.8</u>	<u>1092</u>	<u>1068</u>
Avg	0.358	57.2	1100	1068

10.0 EFFECT OF PLATING A HIGH TENACITY NYLON  
FIBER FELT WITH TWO PERCENTAGES  
OF POLYPROPYLENE FIBER

Armor requirements suggest the possibility that a need might arise for a felt composed of a superior ballistic fiber in the core and plated on either side with a fiber exhibiting excellent formability properties.

In order to investigate the ballistic properties of such a system, felts 5D-1, 5D-2, and 5E-1, 5E-2 (see Table XII) were constructed representing two fiber sandwich combinations of the same fibers.

TABLE XII

**EFFECT OF PLATING A HIGH TENACITY NYLON FIBER FELT  
WITH TWO PERCENTAGES OF POLYPROPYLENE FIBER**

Description of Felt 50/50 Blend

Top Layer - 25% by weight 3 denier 2-1/2 inch polypropylene staple

Core - 50% by weight 6 denier 3 inch T-702 high tenacity uncrimped nylon

Bottom Layer - 25% by weight 3 denier 2-1/2 inch polypropylene

<u>Code</u>	<u>Thickness Before Pressing</u>	<u>Weight Before Pressing</u>	<u>Thickness After Pressing</u>	<u>Weight After Pressing</u>	<u>V-50</u>
5D-1	0.495	64.6	0.353	67.2	903
5D-2	0.468	64.6	-- Not pressed --		915

Description of Felt 70/30 Blend

Top Layer - 15% by weight 3 denier 2-1/2 inch polypropylene staple

Core - 70% by weight 6 denier 3 inch T-702 high tenacity uncrimped nylon

Bottom layer - 15% by weight 3 denier 2-1/2 inch polypropylene staple

<u>Code</u>	<u>Thickness Before Pressing</u>	<u>Weight Before Pressing</u>	<u>Thickness After Pressing</u>	<u>Weight After Pressing</u>	<u>V-50</u>
5E-1	0.386	48.9	0.273	52.7	977
5E-2	0.388	50.2	-- Not pressed --		918

BEST AVAILABLE COPY

11.0 EFFECT OF DECETEX-104 ON BALLISTIC PROPERTIES  
OF HIGH TENACITY NYLON FIBER FELT

Three pre-neededled bats were prepared using T-702 high tenacity nylon fiber, 6 denier, 3 inch uncrimped fiber. Each felt was sprayed with a Decetex-104/water emulsion to a 4% pickup of the 100% product. The three layers were then neededled together three times on each side to produce the final felt.

<u>Code</u>	<u>Thickness</u>	<u>Weight Oz/Sq Yd</u>	<u>V-50</u>
5G-1	.682	72.6	991

Note: Felt 4U-1 reported in Table II, Page 12 was prepared with the same fiber without Decetex application and was made at the same thickness (0.681); however, the weight in oz/sq yd was considerably lower (49.7) and the resultant V-50 was 1129 ft/sec.

BEST AVAILABLE COPY

## 12.0 EFFECT OF SYTON ON BALLISTIC PROPERTIES OF NYLON FELT

Syton, a dispersion of colloidal silica manufactured by the Monsanto Chemical Company, is frequently used as an antislip treatment on various fiber to impart greater fiber to fiber friction properties. In order to assess the value of such a treatment to ballistic resistance, felts 4"Q", 4"R" and 4"P" (see Table II - Nylon) were constructed. In one case, (felt 4"Q") the felt pad prior to needling was sprayed with the commercial product to a 2% add on.

A like quantity of syton was also applied to the fiber prior to carding (felt 4"R"). The third felt was constructed in like fashion without treatment to serve as the control for subsequent comparison.

### 13.0 DEVELOPMENT OF MATHEMATICAL MODEL

Initially, each fiber and felt property was examined individually and combined in many forms in order to find an empirical relationship which appeared to correlate with the V-50 values. It was convenient to utilize the Dacron felts (Table I) for the original work in that an extensive range of both fiber and felt properties was available to us.

Only the results of felts constructed in a normal manner by needling alone were used in the analysis. Variations, such as pressing, testing of two felt thicknesses as one, etc. were cause for excluding the results from the analysis. The aforementioned cases involved only a relatively few points and it was decided that if the results deviated from normal or expected results, it was better to investigate them separately rather than affect the over-all results.

In the application of the formula, it was also concluded that 15 and 24 denier fiber, available only in Dynel, gave V-50 values much lower than anticipated. Only two felts of each of these deniers were manufactured and it appears that the relationship does not hold for heavy deniers, although more work should be done to verify this conclusion.

The nominal range of deniers from 1.0 to 6.0 denier did not seem to influence the results. The results obtained on

Polypropylene, Verel, Acetate, Viscose and Vinal fiber felts were not included as sufficient data was not available.

BEST AVAILABLE COPY

## 14.0 MATHEMATICAL MODEL

The equation judged to be best is as follows:

$$V = \log e^{4t} \sqrt{A_D W_i}$$

where V = velocity (V-50) in feet per second

e = base of natural log = 2.71828

t = thickness in inches

$A_D$  = areal density, oz/sq yd

$W_i$  = toughness index =  $\frac{PE}{2}$  where P = tenacity, grams/denier

E = strain

This equation was converted to logarithms for ease of analysis and regression equations for each fiber were determined using the method of least squares.

The results of the analysis expressed in logarithms are listed below:

Least square regression lines

Nylon  $\hat{y} = 2.676265 + 0.163524x$

Zefran  $\hat{y} = 2.589712 + 0.206256x$

Dacron  $\hat{y} = 2.633044 + 0.172792x$

Dynel  $\hat{y} = 2.627756 + 0.206256x$

Orlon  $\hat{y} = 2.769093 + 0.08360x$

Regression was found to exist for all lines using the "t" test at 95% probability.

The mean square deviation from regression was calculated for each equation.

Correlation coefficients ( $r$ ) and the percent of variation explainable by regression ( $r^2$ ) or coefficients of Determination were calculated.

<u>Fiber</u>	<u><math>S^2Y.X</math></u>	<u><math>r</math></u>	<u><math>r^2\%</math></u>	<u>No. of Samples</u>
Nylon	0.000331	0.802	64.3	22
Zefran	0.000360	0.892	79.5	15
Dacron	0.000766	0.661	43.6	25
Dynel	0.000004	0.988	98.8	4
Orlon	0.000288	0.703	49.9	8

It can be seen that there is a high degree of correlation between velocity and the calculated formula and a relatively large amount of the variability is explained by the regression.

#### 14.1 Example Illustrating Application of Formula

Utilizing felt M-2 Dacron Table I

$$V = \log e^{4t} \sqrt{W_i A_D}$$

$$t = 0.346 \text{ inches (Thickness)}$$

$$4t = 1.384$$

$$e^{4t} = 3.975$$

$$A_D \text{ (Areal Density)} = 38.2 \text{ oz/sq yd}$$

P (Tenacity) = 4.81 grams/denier (Table XIII)

E (Strain) = 0.389 (Table XIII)

$$W_i = \frac{PE}{2} = \frac{(4.81)(0.389)}{2} = 0.936$$

$$V = \log e^{4t} \sqrt{W_i A_D} = \log [3.975 \sqrt{(38.2)(0.936)}] = 1.377$$

The "V" value obtained (1.377) is in terms of fiber and felt properties and actually represents the x values in the equations listed (Least Square Regression Lines) on Page 35.

$$\text{Dacron: } \hat{y} = 2.633044 + 0.172792x$$

$$\hat{y} = 2.633044 + 0.172792 (1.377)$$

$$\hat{y} = 2.864067$$

" $\hat{y}$ " is the predicted velocity of the felt and as it is a log, it must be converted.

$$\hat{y} = 731 \text{ ft/sec (predicted)}$$

The felt actually had a V-50 of 725 ft/sec.

#### 14.2 Analysis of Variance

An analysis of variance and analysis of covariance was used to determine if the means of x and of y (V-50 and formula) differed; if the slopes of the lines were alike; and if the adjusted means (elevations) were alike.

TABLE XIII

BREAKING STRENGTH, ELONGATION AND WORK INDEX  
OF MAJOR FIBERS EVALUATED

<u>Fiber</u>	<u>Denier</u>	<u>Tenacity grams/denier</u>	<u>Elonga- tion/100</u>	<u>Wi (Work Index)</u>
Orlon	1	2.74	.1953	.268
	2	2.67	.2804	.374
	3	2.67	.3025	.404
	6	2.60	.393	.510
Dynel	3	3.10	.336	.520
	6	2.75	.379	.521
	15	.746	.953	.355
	24	2.14	.431	.462
Nylon	1 1/2	4.30	.408	.877
	3	3.97	3.40	.675
	6	4.70	.436	1.025
Zefran	3	2.96	.273	.404
	6	2.28	.303	.345
Dacron	1.5	5.051	.3905	.986
	3.0	4.811	.3893	.936
	4.5	4.472	.4818	1.027
	6	3.57	.3180	.577

The following results were obtained:

	<u>F calc</u>	<u>F 05</u>	<u>F 01</u>
V-50 (y) means	25.03	2.53	4.13
Formula (x) means	19.39	2.53	4.13
Regression coefficient (slopes)	1.23	2.53	4.13
Adjusted means (elevation)	5.32	2.53	4.13

The slopes of the lines were found to be alike (parallel), however, the elevation (intercept) and the x and y averages were found to be not alike. The differences obtained in the y (V-50) means and subsequently the x (formula) means were expected as no attempt was made to make a range of felts for each fiber which would have a common V-50 range. It is possible that if a complete range of felts could have been made for all fibers, a common elevation would have occurred.

While the above analysis tends to preclude the use of a common equation to represent all fibers, such an equation might be useful in estimating approximate results of felts made from fibers for which no equation is available. Using the seventy-four samples in a single regression analysis, the following equation was determined:

$$y = 2.590994 + 0.206852x$$

$$\text{with } s^2_{y.x} = 0.000602$$

$$r = 0.877$$

$$r^2\% = 76.9$$

BEST AVAILABLE COPY

Using one sample of Verel and one sample of Viscose to evaluate the equation, the following results were obtained:

<u>Fiber</u>	<u>Denier</u>	<u>Predicted V-50</u>	<u>Actual V-50</u>
Verel	3	768	690
Viscose	5.5	749	761

While two tests are not considered sufficient to indicate the usefulness of this equation, the results do suggest that it is worthy of further study.

As thickness of the felt is such an important factor in the V-50 results, it is our opinion that more work should be done to establish a proper procedure for measurement of this parameter.

## 15.0 CONCLUSIONS

Based upon an analysis of the felts constructed and listed in Tables I - VI, the following conclusions were reached. There is poor correlation between V-50 values and fiber length, fiber denier, fiber crimp and felt weight. A reasonably good correlation exists between V-50 values and felt thickness, and there is, likewise, a significant variation in V-50 values from one type fiber felt to another. In the case of the latter, it appears that fiber tenacity or fiber toughness index ( $\frac{PE}{2}$  where P-Tenacity, E = Strain) enables one to rank the V-50 differences between fibers.

It is apparent that no direct correlation exists between the force necessary to penetrate the felts at low speed and the V-50 test (Table VII). Also, air permeability values obtained on selected felts were in poor agreement with V-50 values (Table VIII).

Conflicting results were obtained as to the effect of heatsetting and pressing of nylon felts. However, there is sufficient evidence to conclude that reducing the thickness by pre-heating and pressing tends to decrease the V-50 values although relatively slight in comparison to the thickness change. (See Felts 4U 1 and 4U 2, 4V 1 and 4V 2, 4T 1 and 4T 2 - Table II and Table IX.) Furthermore, it was established that there was a 5 to

6% growth of pressed felts after three weeks' storage under standard textile laboratory conditions (70° - 65% R.H.). (See Felts 5H-1, 5H-2, 5H-3 - Table X.)

A comparison of felts made experimentally with felts produced commercially revealed insignificant differences in V-50 values; also that ballistic ratings between different V-50 ranges were apparently in good agreement.

• The addition of Decetex 104 to the fiber appears to enhance the needling qualities in that it lubricates the fibers making it possible to achieve considerable weight in the felt. However, V-50 values were significantly lowered. The addition of syton to the fiber prior to carding appears to improve the ballistic resistance to a small degree although additional experiments would have to be performed to establish this as fact.

## 16.0 RECOMMENDATION FOR FUTURE STUDY

Based upon the experience gained in this study, it appears that future programs might give greater consideration to the following points.

1. Random orientation of fiber webbings or isotropic felts would appear to be advantageous.

2. A study of various methods of felt thickness measurement may be necessary to improve the reliability of the mathematical model.

3. The incorporation of anti-slip compounds such as colloidal silica (syton) to the fiber or felt is deserving of more study.

4. Appropriate felting needles for the production of heavy and thick felts from 1 1/2 denier and finer fiber should be determined so that impact resistance of felts of this type can be established.

5. A concerted study of blends of two or more fibers might prove advantageous with particular emphasis on the use of a high shrink fiber with a low shrink, high tenacity fiber.

6. The reinforcement of the fiber felt with layers of ballistic fabric now available might prove of interest.

7. The incorporation of varying amounts and types of adhesives employing various methods of distribution to form felts

with and without needling should be investigated.

BEST AVAILABLE COPY